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Evaluation of Supercritical Cryogen Storage and Transfer Systems for Future NASA Missions

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EVALUATION OF SUPERCRITICAL CRYOGEN STORAGE AND TRANSFER SYSTEMS FOR FUTURE NASA MISSIONS

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Abstract

Conceptual designs of Space Transportation Vehicles (STV), and their orbital servicing facilities, that utilize supercritical, single-phase, cryogenic propellants have been established and compared with conventional subcritical, two-phase, STV concepts. The analytical study was motivated by the desire to avoid fluid management problems associated with the storage, acquisition and transfer of subcritical liquid oxygen and hydrogen propellants in the low-gravity environment of space. Although feasible, the supercritical concepts suffer from STV weight penalties and propellant resupply system power requirements which make the concepts impractical.

Nomenclature

g	acceleration due to gravity, 32.2 ft/sec^2
H	total enthalpy, Btu
h	specific enthalpy, Btu/lb
I	specific impulse, sec
M	total mass, lb
n	summation integer
P	gage pressure, psig
V	internal volume, in.^{3}
Δm	incremental mass, lb
ΔV	velocity increment, ft/sec
ρ	density, lb/ft^3

Subscripts:

b	burst
r	receiver tank
s	supply tank
1	initial
2	intermediate or final

Background

Fluids are generally thought to exist only in the three common thermodynamic states of solid, liquid and vapor (e.g., ice, water and steam). However, under certain conditions, particularly elevated pressure or temperature, the physical distinction between the liquid and vapor phases disappears and the resulting single phase fluid is identified as being in a supercritical state.

The supercritical fluid phenomena will be better understood by referring to Fig. 1, which shows a pressure versus specific volume plot for a typical fluid. Imagine a closed container, of fixed volume, partially filled with liquid and the remaining space being occupied by vapor (point A). Because the container volume and fluid mass, liquid plus vapor, are constant, the system specific volume is also a constant. This two phase thermodynamic state is called the subcritical region. If heat is added to the container, the system temperature and pressure will increase with the fluid system process following a line of constant specific volume. As the temperature of the liquid increases, it expands and its density is reduced. In contrast to the liquid, the vapor is highly compressible and thus its density increases as the pressure rises. Eventually, the density of the liquid and vapor become identical and the distinction between the two phases disappears (point B). The critical point (C) is the intersection of the lines of constant (critical) temperature and constant (critical) pressure above which only single phase fluid can exist. The region of fluid thermodynamic states above either the critical pressure or critical temperature is referred to as the supercritical region.

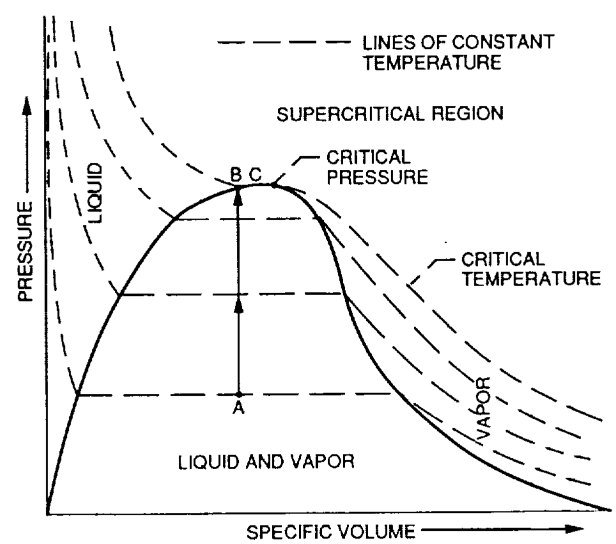


Figure 1. - Typical fluid property characteristics.

For space applications, supercritical cryogenic fluid storage and supply systems have the advantages associated with the containment of a single phase, relatively high density, fluid (compared with high pressure gas storage) which minimizes tank volume. More importantly, the existence of a single-phase fluid avoids the low-gravity subcritical system problems associated with separating the two phases so that preferential liquid withdrawal or vapor venting can be accomplished.

The obvious disadvantage of supercritical systems is the high pressure levels required which translates directly into greater system weight. Supercritical conditions exist for hydrogen at pressures above 187.5 psia; for oxygen this pressure is

731.4 psia. In order to insure that the cryogen storage systems do not become subcritical, supercritical hydrogen storage tanks typically operate at pressures of at least 200 psia and oxygen storage is typically above 800 psia. Less obvious disadvantages of supercritical systems are associated with the need to maintain the required supercritical pressure level, as fluid is withdrawn from the system, by adding energy to the tankage, usually in the form of heat. For some applications, there is also a disadvantage resulting from the fact that the fluid is continually decreasing in density (mass is being removed from a constant volume system) and increasing in enthalpy (due to the heat addition required to maintain pressure) thus reducing the fluids cooling capability.

Introduction

Supercritical cryogenic fluid storage systems were first employed for space applications, during the Gemini and Apollo programs.[1] Subsequently, similar systems were developed for use on the Space Shuttle as a means to provide oxygen vapor to the life support system and both hydrogen and oxygen vapor to be utilized as fuel cell reactants for the generation of electrical power. Currently, the use of supercritical nitrogen storage systems has been baselined for Space Station Freedom to provide make-up gas for the environmental control system.

The in-space use of supercritical cryogen storage and supply systems has thus far been restricted to applications which use the fluid in the vapor state at approximately room temperature. Consequently, the changing density and enthalpy of the fluid as it leaves the storage tank are irrelevant because the pressure is reduced and the fluid is heated to the desired vapor state external to the storage tank. In addition, the heat input required to maintain the storage tank pressure reduces the external heat input requirements so that only the weight associated with the high pressure supercritical storage system is a true penalty when compared with a subcritical system that would perform the same function.

Many future space missions will require the on-orbit resupply of high-density cryogenic fluids to not only minimize spacecraft volume, but to also provide cooling capability. Examples of spacecraft designed to enable these future missions are the family of Space Transfer Vehicle (STV) concepts that are being developed by NASA and the aerospace industry. These propulsive vehicles utilize the cryogenic propellants as coolants for the engines prior to their being combusted in the thrust chambers.

The objective of the analytical effort described herein was to assess the feasibility of employing a supercritical cryogen storage and transfer system, as well as a STV utilizing supercritical cryogen tankage, to meet future NASA space transportation system needs. Two subcritical STV concepts developed by the Boeing Aerospace Co.[2] were used for comparison with the supercritical system concepts. One Boeing STV concept had a dry weight of 7500 lb, a LOX/LH_2 propellant loading of 46 800 lb and was designed to transport a 14 600 lb spacecraft from low-earth-orbit (LEO) to geosynchronous orbit (GEO); only the vehicle returns to LEO, utilizing aerobraking to minimize return propellant requirements. The second Boeing STV concept provided a LEO to GEO to LEO round-trip payload capability of 12 000 lb, utilizing 70 200 lb of LOX/LH_2 propellants and aerobraking.

Supercritical transfer system concepts analyzed involved the option of cooling the STV propellants, either in the STV tankage or the transfer line, to increase the fluid density, and cooling capacity. Weight estimates for the supercritical STV concepts were established which included either conventional high pressure aluminum tankage or advanced technology tanks fabricated with a thin aluminum liner overwrapped with graphite fibers.

Analytical Approach

Properties of Transferred Supercritical Fluids

Thermodynamic analysis, which can be performed on a unit volume basis and is thus independent of system size, was first performed to establish the density and enthalpy of the fluid which is withdrawn from the supercritical hydrogen and oxygen storage systems as a function of the mass fraction of the fluid remaining in the storage tank. The initial conditions in the supercritical supply tanks were established by assuming that the tanks are loaded to a 98 percent fill level, prior to launch, with cryogens saturated at atmospheric pressure. The supply tanks are then locked up and allowed to self-pressurize to 250 and 850 psia for the hydrogen and oxygen tanks, respectively. The hydrogen and oxygen receiver tanks are assumed to operate at 200 and 800 psia, respectively, so that the whole system is always above the critical pressure and a 50 psia pressure differential is available to enable the fluid transfer process to proceed. As fluid is withdrawn from each supply tank, heat must be added to maintain the desired pressure level and the temperature of the remaining fluid increases.

The system analysis was performed by taking incremental changes in supply tank temperature, and then consulting data handbooks[3,4] to establish the new density and enthalpy of the fluid remaining in the supply tank. The step sizes are kept relatively small based on changes in density to improve accuracy. The mass of fluid that had to be removed and the change in energy of the fluid remaining (both on a supply tank unit volume basis) were calculated as follows:

$$\frac{\Delta m}{V_s} = \rho_1 - \rho_2 \qquad (1)$$

$$\frac{\Delta h_s}{V_s} = \rho_2(h_2 - h_1) \qquad (2)$$

The incremental energy input to each supply tank, as a function of the incremental fluid mass removed, can then be calculated:

$$\frac{\Delta h_s}{\Delta m} = \frac{\Delta h_s}{V_s} \cdot \frac{V_s}{\Delta m} = \frac{\rho_2(h_2 - h_1)}{\rho_1 - \rho_2} \qquad (3)$$

The iterative analysis was continued until 90 percent of the fluid mass had been removed from each supply tank. Summing the incremental values of $\Delta h_s/\Delta m$ provides the total energy input, per unit mass of fluid transferred, that must be added to each supply tank. In the case of the hydrogen

storage tank, 146 Btu's/lb of supercritical fluid transferred are required and 63 Btu's/lb of fluid transferred are required for the supercritical oxygen storage tank.

The properties of the supercritical fluid which is accumulating in each receiver tank can also be established by a similar iterative process. The energy transferred with each incremental mass of supercritical fluid is equal to the product of the incremental mass and its average enthalpy:

$$\frac{\Delta h_r}{V_s} = \frac{\Delta m}{V_s}\left(\frac{h_2 + h_1}{2}\right) \tag{4}$$

The total energy contained in the transferred supercritical fluid is equal to the sum of the incremental energy additions to each receiver tank:

$$\frac{H_r}{V_s} = \sum_{n=1}^{n} \frac{\Delta h_r}{V_s} \tag{5}$$

The total mass transferred to each receiver tank is equal to the sum of the incremental masses:

$$\frac{M_r}{V_s} = \sum_{n=1}^{n} \frac{\Delta m}{V_s} \tag{6}$$

The average enthalpy of the fluid accumulated in each receiver tank is then equal to the total energy contained in the transferred supercritical fluid divided by the total mass of fluid transferred:

$$\overline{h_r} = \frac{H_r}{V_s} \cdot \frac{V_s}{M_r} \tag{7}$$

For each fluid transfer system, the previously selected receiver tank pressure and the above calculated average enthalpy can be used to enter the corresponding fluid property data base to establish the fluid density in each receiver tank. The fluid densities in the respective supply and receiver tanks can be used to establish the ratio of receiver to supply tank volume required for each supercritical cryogen transfer system:

$$\frac{V_r}{V_s} = \frac{\rho_s}{\rho_r} \tag{8}$$

For the supercritical hydrogen transfer system, a receiver tank 83 percent larger than the supply tank is required. The supercritical oxygen receiver tank is 66 percent larger than the supply tank.

An alternate approach involves cooling the supercritical fluid entering each receiver tank to increase its density and thus reduce the size of the required receiver tanks. For this portion of the analysis it was assumed that the supply and receiver tanks would be of equal volume. Since it was earlier assumed that 90 percent of the contained fluid would be removed from each supply tank, the receiver tank fluid density must be 90 percent of the supply tank fluid density. For each receiver tank, the known pressure and fluid density allow determination of the resulting fluid enthalpy. This final receiver tank fluid enthalpy is then subtracted from the previously determined average enthalpy of the transferred fluid, Eq. (7), to establish the cooling required for each supercritical fluid transfer system. For the hydrogen system, 69 Btu's of cooling are required for each pound of supercritical fluid transferred, while 28 Btu's of cooling per pound of supercritical fluid transferred are required for the oxygen system.

Tankage Weight Estimates

Specification of tank pressures and the desired supercritical hydrogen and oxygen densities is all that is required to initiate the structural analysis of the receiver tanks. Tankage designed to accommodate STV total propellant loadings ranging from 40 000 to 80 000 lb were analyzed, assuming a 6 to 1 ratio of oxygen to hydrogen propellant mass. Once the corresponding range of required tank volumes had been established, conventional geometric relationships were employed to determine the required tank configurations. The only constraint on the tank geometry analysis was that tank diameters not exceed 14 ft in diameter so that the resulting STV concepts could be transported to orbit in the Space Shuttle cargo bay.

Although a number of criteria, including dynamic pressure during launch and fracture mechanical fatigue life requirements, can drive tankage design, only static pressure conditions were considered to establish the required tank wall thicknesses. For the aluminum tanks (AL2219-T87) weights were determined by calculating minimum membrane thicknesses based on the greater of the hoop or longitudinal stresses for the cylindrical portion, and the greater of the apex or the equator thicknesses for the dome portion. Standard equations for membrane sizing were taken from Ref. 5. In addition, the larger of the cylinder and dome thicknesses resulting from the ultimate or yield material properties, considering safety factors of 2.0 and 1.5, respectively, were included in the weight calculations. For the graphite epoxy metal lined tanks, weights were calculated by means of a "performance factor", a factor which incorporates all the basic parameters of a composite fiber/metal pressure vessel, namely, burst pressure, internal volume and total vessel weight. The performance factors used for this study were obtained from Ref. 6.

Aluminum tank weights for both conventional subcritical (30 psia) and supercritical cryogen storage systems were determined using stress analysis. The calculated tank wall thicknesses based on the ultimate material properties are always greater, for the selected aluminum material, than the thicknesses required by a yield criteria. Consequently, the ultimate criteria was used to establish tank wall thickness. In addition, the material thickness required at the apex of a tank dome is always greater. Although real tanks would probably have varying tank wall thicknesses on the domes, a conservative approach was employed which assumed a uniform tank dome wall thickness at the maximum calculated value. There will also be local beef-ups of the tankage wall at the junction of the dome to the barrel section to reduce the discontinuity stresses, and at the penetration of the tankage wall for plumbing and electrical/instrumentation wiring.

To account for this, a margin of 15 percent has been included in the tankage weight calculations.

The most satisfactory method of establishing the weights of composite fiber/metal pressure vessels of various configurations is to incorporate all their basic parameters by means of a performance factor (P.F., in inches):

$$P.F. = \frac{P_b V}{M} \tag{9}$$

This factor has an advantage over other design rating methods in that complete vessels (bosses, weld lands, local reinforcements, liners for composite pressure vessels, etc.) are rated by a single term, so that a variety of designs can be compared directly. The best designs are indicated by the highest performance factors.

From Ref. 6, the pressure vessel performance factor for a graphite/aluminum tank is in the range of 800 000 to 1 000 000 in. For this study, the lower value of the performance factor was used to provide a consistent conservative approach. From this simple analytical technique, total supercritical cryogen storage system weights can be calculated for any tank volume and burst pressure. A factor of safety of 2.0 is also used in the composite tank analysis to convert operating pressure to burst pressure. The results of the tankage weight estimate analysis are presented in Figs. 2 and 3 for the hydrogen and oxygen receiver tanks, respectively.

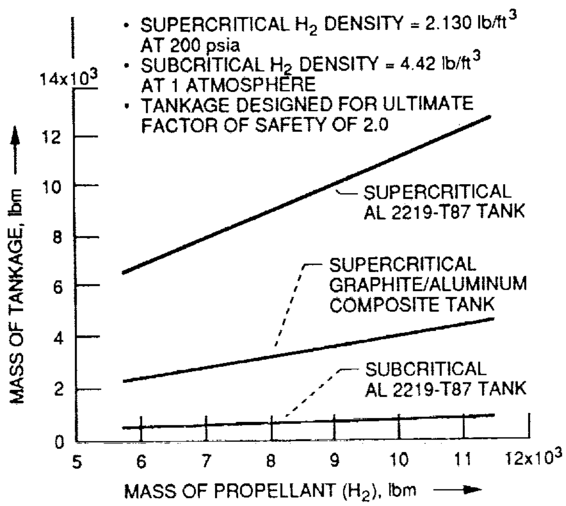


Figure 2. - Hydrogen tankage weight comparison.

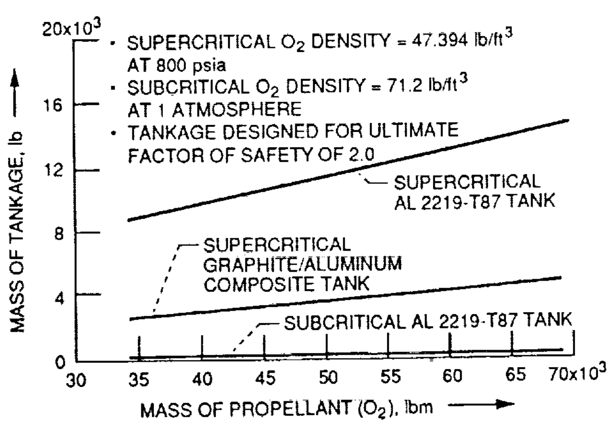


Figure 3. - Oxygen tankage weight comparison.

STV Weight Estimates

The difference between subcritical and supercritical STV concept weights is primarily associated with differences in the required tankage weight. However, the two Boeing concepts were used to establish the functional relationships between nontankage component/subsystem weights and vehicle size. Component and subsystems were categorized into three classes: (1) mission dependent (independent of vehicle size) such as power, control, guidance and navigation subsystems; (2) tankage volume dependent, such as tank insulation and debris/micrometeoroid protection; and (3) tankage mass dependent, such as structure and propulsion subsystems.

For all of the variable weight nontankage components, linear functional relationships between the component/subsystem weights and tankage weight or volume were established. Total supercritical STV weights could then be estimated by summing the individual component and subsystem weights. The analysis was performed for the two pairs (LOX and LH_2) of propellant densities, derived from the thermodynamic analysis, and total STV propellant loadings between 40 000 and 100 000 lb.

STV Payload Placement Capability

The classical rocket equation was used to perform the comparative analysis of subcritical and supercritical STV concepts:

$$\Delta V = I g_o \ln\left(\frac{M_1}{M_2}\right) \tag{10}$$

For the comparison of any two STV concepts, it was assumed that the vehicles would perform the same mission and have identical engine performance characteristics so that the ΔV and the propulsion system specific impulse (I) were assumed to be constants. Consequently, the vehicle comparisons required only that the ratio of M_1 (total initial vehicle and payload mass including propellants) to M_2 (vehicle dry weight + payload) be equal for any pair of STV concepts under evaluation.

The comparative analysis was performed for two different STV design approaches. The first approach involved dictating equal propellant mass, for the pair of STV's being compared, so that M_2 must be a constant to maintain the ratio of M_1 to M_2 constant. With M_2 held constant, any change in STV dry weight must be counterbalanced by an equal and opposite change in payload weight. The second approach involved dictating equal payload placement capability, for the pair of STV's being compared, and performing an iterative calculation of the change in required propellant mass and corresponding vehicle dry weight until equal values of the ratio of M_1 to M_2 were established.

Supply Tank Heat Addition Requirements

The energy addition required to maintain constant supply tank pressure was calculated by multiplying the heating requirements per pound of propellant transferred, both hydrogen and oxygen, times the vehicle propellant mass requirements determined by the analysis discussed previously.

Propellant Cooling Requirements

Total energy removal requirements for the supercritical STV concepts that employed propellant

cooling to reduce tankage size and weight were also established. As in the previous section, this was accomplished by multiplying the cooling requirements per pound of propellant transferred, both oxygen and hydrogen, times the vehicle propellant mass requirements. These supercritical oxygen and hydrogen propellant cooling requirements could be provided by refrigeration or the use of thermodynamic vent system (TVS) subcoolers which utilize the sacrificial boil-off of the corresponding fluid.

Comparison of the propellant cooling requirements with the cooling capability provided by using TVS subcoolers, which employ the sacrificial vaporization of additional propellant provided by the storage and supply system, indicated that slightly more than 1 lb of propellant would need to be discarded for every pound of propellant transferred. This approach suffers from the fact that heating the supply tank, to maintain the required supercritical pressure level, continually increases the fluid enthalpy and reduces its cooling capability as the transfer operation proceeds. The propellant losses associated with the TVS subcooler option for propellant cooling were obviously excessive; consequently, this approach was dropped from further consideration.

The possibility of employing refrigerators to provide the necessary cooling requires that some assumptions be made regarding the availability of advanced technology when required. The first assumption involved projections of attainable efficiency of 1 percent for the hydrogen refrigeration system and 4 percent for the oxygen refrigeration system. These efficiencies represent an increase, by a factor of approximately two, in the performance of refrigeration systems currently under development for space applications.

Once refrigerator efficiencies had been selected and the propellant cooling requirements established, electrical energy requirements could be determined. Electrical power system requirements can then be calculated by dividing the necessary electrical energy by a selected STV propellant loading interval. Typically subcritical STV propellant loading times are assumed to be 8 hr or less. However, the electrical power system required to support a one shift supercritical STV servicing operation would have to have several megawatts of capability. Consequently, in order to reduce the electrical power requirements to more reasonable levels, a 1 week supercritical STV propellant resupply scenario was assumed. The resulting electrical power system requirements are on the order of a few hundred kilowatts and thus are in the realm of possibility (Space Station Freedom initial operating capability is 75 kW). In addition, the waste heat from the refrigerators is more than adequate to provide the necessary heat addition to the supply tanks. On the other hand, the corresponding total refrigeration capability required is still approximately two orders of magnitude greater than any system currently under development for space applications.

Study Results

The results of the supercritical STV weight estimation using AL2219 and graphite/epoxy tanks, along with the data points for the two Boeing concepts, are presented in Figs. 4 and 5, respectively. Detailed subsystem weight comparisons for the two Boeing STV concepts and STV's utilizing supercritical propellant storage are provided in Table 1 (Conventional Aluminum Tankage) and Table 2 (Graphite/Aluminum Composite Tankage). Figure 6 provides a comparison of the total STV weights using graphite/aluminum tankage for the constant propellant and constant payload scenarios.

By reference to Figs. 4 and 5 and Tables 1 and 2, it quickly becomes obvious that any supercritical STV concept based on conventional tankage technology is impractical. The growth in the all aluminum tankage weight, to accommodate the supercritical tank pressures, exceeds the payload weight of either STV concept by a factor of approximately two. Thus, even with no payload, the supercritical

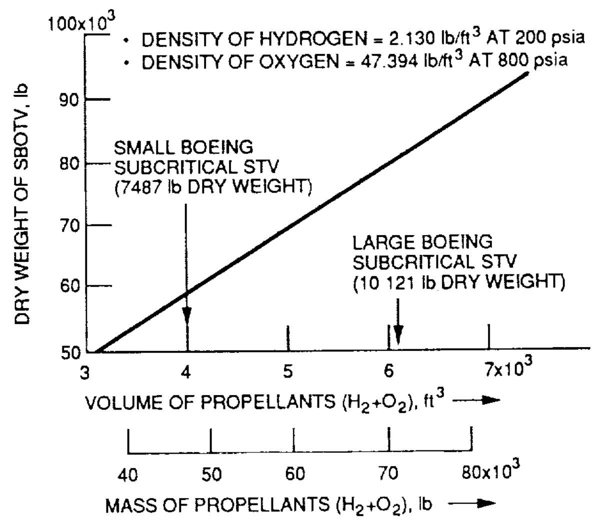


Figure 4. - Supercritical storage (AL 2219-T87 tanks).

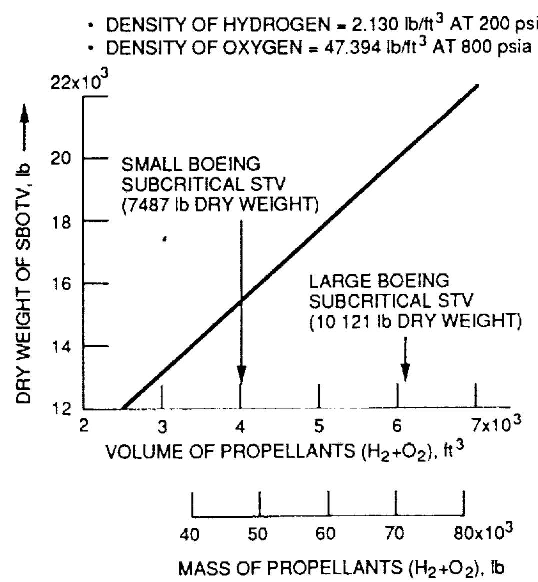


Figure 5. - Supercritical storage (graphite/aluminum composite tanks).

TABLE 1. - SUBCRITICAL (BOEING) AND SUPERCRITICAL[a] STORAGE STV WEIGHT COMPARISON

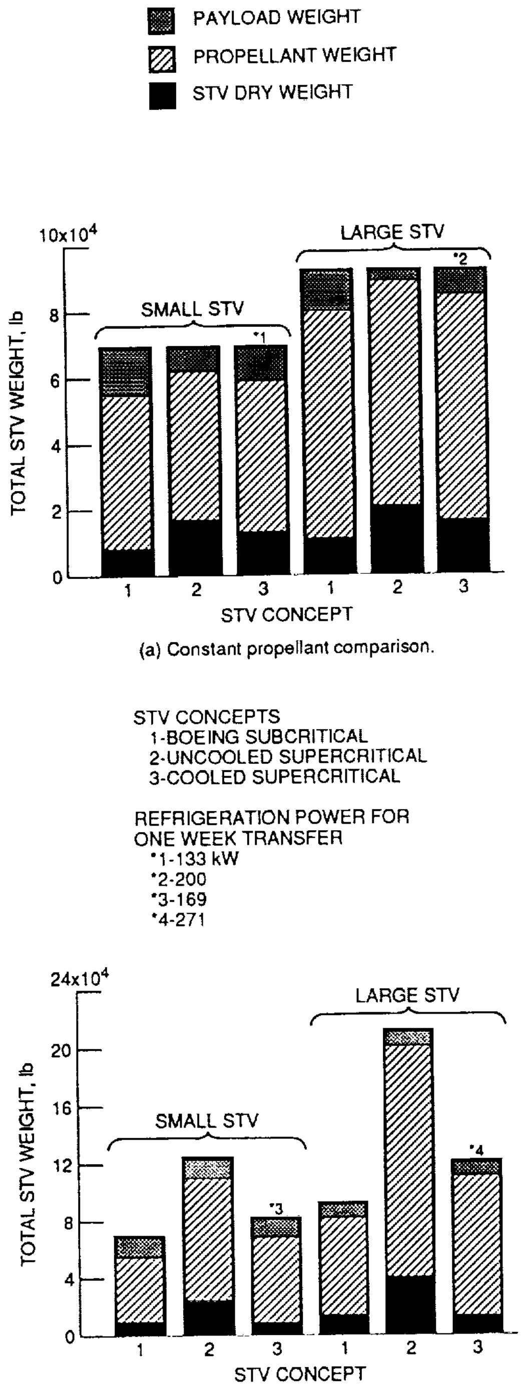
Weights	Small Boeing subcritical	Large Boeing subcritical	Supercritical				
Volume of propellant, ft^3	2 076	3 143	3 405	4 257	5 108	5 960	6 812
Mass of propellant, lb	48 800	70 874	40 000	50 000	60 000	70 000	80 000
Structures and mechanisms							
Body structure	1 058	1 107	3 242	3 689	4 126	4 598	5 068
Tankage	859	1 187	15 477	18 467	21 397	24 554	27 699
Met/Deb protection	276	384	553	663	776	827	899
Aeroassist device							
Structure	938	1 703	10 372	12 186	13 964	15 879	17 787
Thermal protection	478	964	6 017	7 074	8 110	9 226	10 388
Thermal protection and control	496	621	651	753	855	957	1 058
Main propulsion, less engines	508	586	3 984	4 695	5 392	6 143	6 891
Main engines (2-6000 LBF ASE)	428	428	428	428	428	428	428
Auxiliary propulsion	407	463	2 902	3 413	3 913	4 452	4 989
Guidance and navigation	134	154	154	154	154	154	154
Communications and data handling	422	521	521	521	521	521	521
Electrical power	544	730	730	730	730	730	730
Weight growth, 15 percent	939	1 273	6 755	7 916	9 055	10 270	11 484
Dry weight, lb	7 487	10 121	51 786	60 689	69 421	78 739	88 046

[a]AL2219-T87 tank.

TABLE 2. - SUBCRITICAL (BOEING) AND SUPERCRITICAL[a] STORAGE STV WEIGHT COMPARISON

Weights	Small Boeing subcritical	Large Boeing subcritical	Supercritical				
Volume of propellant, ft^3	2 076	3 143	3 405	4 257	5 108	5 960	6 812
Mass of propellant, lb	48 800	70 874	40 000	50 000	60 000	70 000	80 000
Structures and mechanisms							
Body structure	1 058	1 107	1 290	1 470	1 476	1 560	1 650
Tankage	859	1 187	2 408	3 011	3 655	4 216	4 819
Met/Deb protection	276	384	553	663	776	827	899
Aeroassist device							
Structure	938	1 703	2 443	2 809	3 199	3 540	3 905
Thermal protection	478	964	1 395	1 609	1 836	2 035	2 248
Thermal protection and control	496	621	651	753	855	957	1 058
Main propulsion, less engines	508	586	877	1 020	1 173	1 307	1 450
Main engines (2-6000 LBF ASE)	428	428	428	428	428	428	428
Auxiliary propulsion	407	463	671	774	884	980	1 083
Guidance and navigation	134	154	154	154	154	154	154
Communications and data handling	422	521	521	521	521	521	521
Electrical power	544	730	730	730	730	730	730
Weight growth, 15 percent	939	1 273	1 818	2 091	2 353	2 588	2 842
Dry weight, lb	7 487	10 121	13 939	16 033	18 040	19 843	21 787

[a]Graphite/aluminum composite tank.



(a) Constant propellant comparison.

(b) Constant payload comparison.

Figure 6. - STV weight comparison using graphite/aluminum tankage.

STV concepts utilizing conventional tank design practices would not be capable of making a LEO to GEO roundtrip mission. Consequently, the remainder of the discussion of the study results is based on the assumption that large high pressure cryogenic tank fabrication technology can be developed, employing an aluminum liner with graphite fiber overwrappings for the supercritical STV concepts.

Comparison of Small STV Concepts

The Boeing subcritical STV concept, designed to place a 14 600 lb payload in geosynchronous orbit, has a dry weight of 7500 lb and requires 46 800 lb of liquid oxygen and hydrogen propellants. A supercritical STV with the same uncooled propellant mass would have a dry weight of 15 900 lb (Fig. 5) reducing the vehicle payload placement capability to 6200 lb. Cooling the supercritical propellants during the transfer process, to increase propellant density and thus reduce tankage volume and mass, yields a STV dry weight of 12 000 lb with a 10 100 lb payload placement capability. A 133 kW electrical power system would be required to provide the necessary refrigeration capability during a 1 week transfer operation.

A supercritical STV concept, which employs the propellant cooling technique and has been sized to have the same payload placement capability as the smaller Boeing subcritical STV concept, would require 60 800 lb of cryogenic propellants. For a 1 week propellant loading scenario, a 169 kW electrical power system would be required. A supercritical STV concept without cooling would require 86 100 lb of propellant.

Comparison of Larger STV Concepts

The other Boeing STV concept was designed to provide payload round trip capability between low-earth-orbit and geosynchronous orbit. This vehicle has a dry weight of 10 100 lb and requires 70 200 lb of liquid oxygen and hydrogen propellants for a 12 000 lb payload. A supercritical STV with the same uncooled propellant mass would have a dry weight of 20 500 lb, yielding a low payload transport capability of 1600 lb. Cooling the supercritical propellants during the transfer process would reduce the STV dry weight to 14 500 lb, providing a payload of 7600 lb. Approximately 200 kW of electrical power would be required to accomplish the cooled supercritical propellant transfer operation in 1 week. Similarly, 98 100 lb of cooled cryogenic propellants and a 271 kW power system would be required for a supercritical STV with a 12 000 lb payload transport capability. An uncooled STV would require 161 500 lb of propellant.

For the range of vehicle concepts considered during this study, the supply tank heat addition requirements varied from 1060 to 2150 kWh. If a one shift, 8 hr, STV servicing operation is assumed, then power systems ranging in size from 132 to 269 kW would be required. A more reasonable approach would be to utilize waste heat that would otherwise be diverted to a radiator, and extend the servicing interval to several days.

Concluding Remarks

A supercritical oxygen and hydrogen storage and transfer system could be configured to resupply a supercritical STV. However, current technology is totally inadequate to meet the system needs. The technology for the fabrication of large cryogenic tankage employing aluminum liners overwrapped with graphite fiber, or concepts with comparable capability, would be required. In addition, high capacity cryogenic refrigeration capability for space application would need to be developed (nearly two orders of magnitude greater than any units currently under development).

No attempt was made to assess the impact of utilizing supercritical systems on the earth-to-orbit cryogen transport vehicle (tanker).

Obviously, the supercritical tanker would experience tankage weight growth comparable to the STV and thus would likely also need to employ advanced technology tankage. However, depending on the mode of tanker transport to orbit (Space Shuttle, Shuttle C, ALS) the tanker may be a volume constrained payload, due to the low density of the hydrogen cryogen, and thus the weight penalties may not be too significant.

If an on-orbit Depot is used to accumulate supercritical propellants for periodic servicing of STV's, its tankage would also be significantly heavier than current subcritical orbital cryogen storage and supply concepts. Since the Depot will likely be transported to orbit empty, to optimize thermal performance, and must be launched only once, the weight penalties may not be important. The Depot concept does introduce the need to perform two in-space fluid transfer operations (tanker to Depot and Depot to STV) and the concurrent power requirements for operation of the refrigeration system. However, the same power system and refrigerators could be employed to effect each transfer operation so that no additional hardware would be required.

Much of the justification for STV's, other than reusability, is based on their lighter weight and subsequently smaller propellant requirements, for a given mission and payload, when compared with ground based propulsion vehicle concepts. The supercritical STV concepts are inherently heavier and consequently have less payload placement capability for the same propellant loading. Even the assumption of the availability of advanced materials and refrigeration technology, large power generation capability and the acceptance of a 1 week STV servicing interval is not enough to make the supercritical concept a reasonable alternative to the development of the subcritical cryogenic fluid management technology required to enable current STV concepts to be developed and achieve operational success.

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16. Abstract

Conceptual designs of Space Transportation Vehicles (STV), and their orbital servicing facilities, that utilize supercritical, single-phase, cryogenic propellants have been established and compared with conventional subcritical, two-phase, STV concepts. The analytical study was motivated by the desire to avoid fluid management problems associated with the storage, acquisition and transfer of subcritical liquid oxygen and hydrogen propellants in the low-gravity environment of space. Although feasible, the supercritical concepts suffer from STV weight penalties and propellant resupply system power requirements which make the concepts impractical.

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